# Trends in Optocoupler Radiation Degradation†

T. F. Miyahira and A. H. Johnston
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

## I. INTRODUCTION

Optocouplers are simple devices compared to conventional integrated circuits, but have proven to be somewhat difficult to use in space because they require high internal gain to amplify photocurrent produced by internal light-emitting diodes (net power transfer from the LED to the photodetector is on the order of 0.1%). Space failures have occurred from two different mechanisms: displacement damage from high-energy protons, which produces permanent degradation [1-7]; and transient upsets from heavy ions or protons [8,9]. Transient upset effects are generally important only for optocouplers with high-gain amplifiers, and are expected to be of secondary importance for these devices compared to displacement degradation. Several advances have been made in optocoupler technology that improve performance and reduce input current by more than an order of magnitude. The purpose of the present paper is to evaluate new optocoupler technologies and compare their radiation response with results for older devices.

Four devices were selected for the study, and some key properties are shown in Table 1. Two new optocouplers from Agilent Technologies were evaluated that are designed to operate with unusually low input currents – as low as 40 μA – with Darlington phototransistors for amplification. As shown in the table, both devices have much higher current transfer ratio than older optocouplers. Both devices are low-speed, low power parts with open collector outputs, and do not incorporate high-gain amplifier circuits. A special high-linearity optocoupler that provides matched photocurrents in two photodiodes from a single internal LED was also selected for the study. Tests were also done on several lots of the older 4N49 optocoupler (manufactured by Micropac) in order to determine how the radiation response of this highly sensitive device, which continues to be used in space systems, has varied over a production period of about 7 years.

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Table 1. Properties of the Optocouplers Used in the Study

| Device | Manu-facturer | Input Current (mA) | Current Transfer Ratio | LED Technology |
|---|---|---|---|---|
| 6N139 | Agilent | 0.5 | 20 | Double-heterojunction |
| HCPL-4701 | Agilent | 0.04 | 35 | Double-heterojunction |
| HCNR200 | Agilent | 0.1-10 | 0.005* | Double-heterojunction |
| 4N49 | Micropac | 1 | 2 | Amphoteric |

*This device contains no active gain elements. The current transfer ratio is the current in each of the two photodiodes.

## II. DISPLACEMENT DAMAGE TESTS

### A. Experimental Approach

Testing was done using 50-MeV protons at the University of California, Davis. Devices were irradiated with all pins at ground. They were removed after each exposure run, which took approximately 5 minutes to complete, to measure their electrical properties. Measurements included current transfer ratio (CTR), transistor gain, and special measurements of the photoresponse (essentially the photocurrent in the collector-base region of the phototransistor or photodiode). An Agilent Technologies 4156B parameter analyzer was used to make the measurements, programming the system to enable measurements with an 80 μs pulse length. This limited the total charge during measurements to about 0.1 mC. This was done to reduce interference from injection-enhanced annealing [10,11]. Devices were placed in a temperature controlled test fixture when measurements were made that held the device temperature to 22 ± 0.1 °C to reduce interference from temperature fluctuations over the course of the experiment.

### B. Results for Optocouplers with Low Input Current

The degradation of the two Agilent optocouplers with low input current was very similar. Figure 1 shows results for the HCPL-4701, taken over a range of input currents. The data correspond to the mean of six different devices from the same lot. Several features should be noted. First, CTR varies over a wide range, depending on the LED input current.

Second, the CTR of these devices is much higher than that of conventional optocouplers. Third, these devices are far less affected by radiation damage than the 4N49 optocoupler, in spite of the higher CTR and very low LED input current. The transistor collector current at which the CTR "peaks" moves to higher values as the LED degrades because of the lower photocurrent.

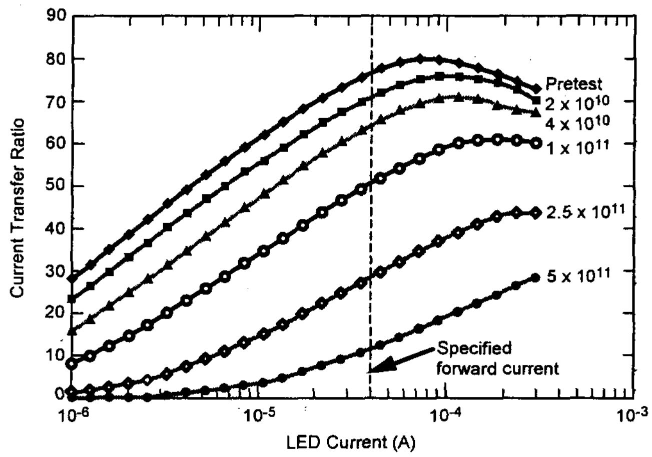


Figure 1. Current dependence of CTR before and after irradiation for the HCPL-4701 optocoupler.

Figure 2 shows the degradation of CTR, photoresponse and transistor gain (normalized) for the HCPL-4701 optocoupler vs. proton fluence. CTR was measured with $I_F = 40\ \mu A$. It is clear from this figure that CTR degradation is considerably greater than gain degradation, even at the relatively high proton fluences that were used in these tests. Photoresponse degradation closely tracks gain degradation, except at the highest radiation levels. This is caused by lifetime degradation in the photodetector [2,6].

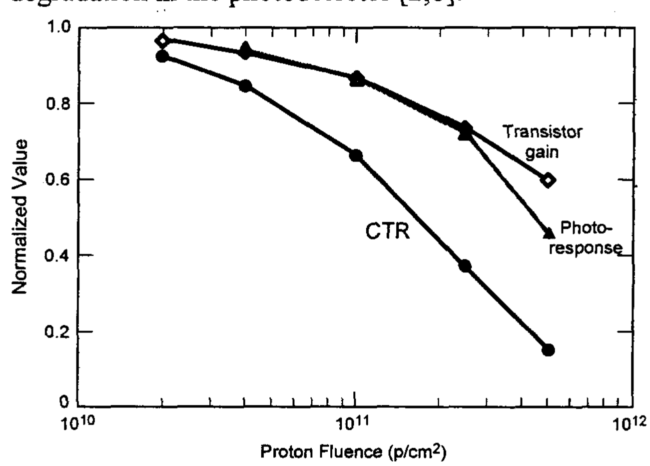


Figure 2. Degradation of CTR, transistor gain and photoresponse for the HCPL-4701 optocoupler.

Results for the 6N139, which has a higher input current rating, were similar to the results for the HCPL-4701 as shown in Figure 3. However, the CTR degradation is approximately a factor of two less for the 6N139 at the highest fluence. The improvement is not due to optical efficiency (see the Discussion section), but is caused by the higher light output of the LED. This raises the operating current of the phototransistor into a region where it operates more efficiently.

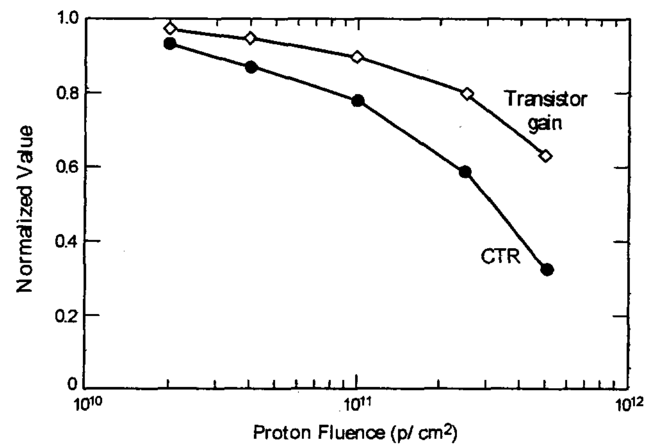


Figure 3. CTR and gain degradation for the 6N139 optocoupler

*C. Results for the Linear Optocoupler*

The linear optocoupler is fabricated with photodiodes, and contains no phototransistors. Thus, measurements of the photodiode current show how the overall photoefficiency of the optocoupler changes with radiation. Figure 4 shows how photocurrent in this device is affected by radiation. Note that the photoresponse of this device is more than two orders of magnitude lower than that of the optocouplers described in the previous section. Degradation of this device is very similar to CTR degradation in the HCPL-4701 (Figure 2), and is dominated by LED degradation, although photoresponse degradation also plays a role.

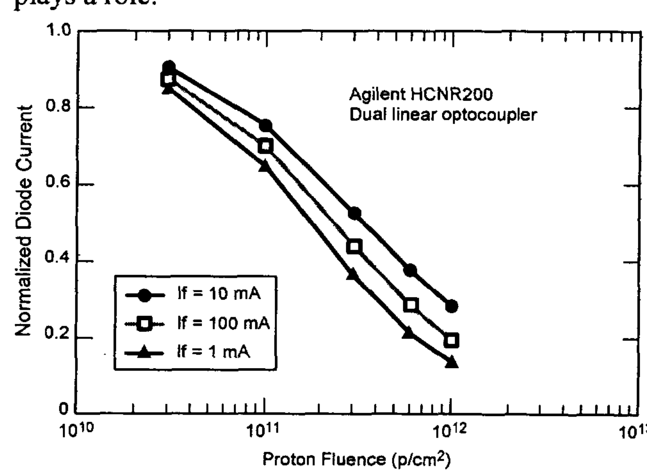


Figure 4. Degradation of photoresponse of the HCP-0200 linear optocoupler (each side of this dual device degrades nearly identically).

The photocurrent of the two photodiodes remained closely matched, even after very high radiation levels.

Matching is a critical parameter for most circuit applications of this device.

*D. Results for the 4N49*

The 4N49 has been frequently used in space systems even though it is extremely sensitive to proton displacement damage. Figure 5 shows the normalized degradation of CTR, photoresponse, and transistor gain for a recent lot of devices from Micropac. Degradation of the 4N49 CTR does not track the photoresponse degradation as closely as for the Agilent device in Figure 2, even though the 4N49 uses an LED technology that is far more sensitive to proton damage [2]. The reason for this is the decrease in phototransistor gain as the LED output reduces the operating current of the phototransistor to the point where it is less efficient. The peak gain of the phototransistor in the 4N49 occurs at currents that are considerably greater than the operating current with $I_F = 1$ mA, increasing the importance of the current dependence of transistor gain in the overall performance of that device type. Even though (electrical) gain degradation at fixed injection changes very little (measured electrically with external base current), the response of the optocoupler is markedly affected by the decreased injection level that occurs as the LED degrades.

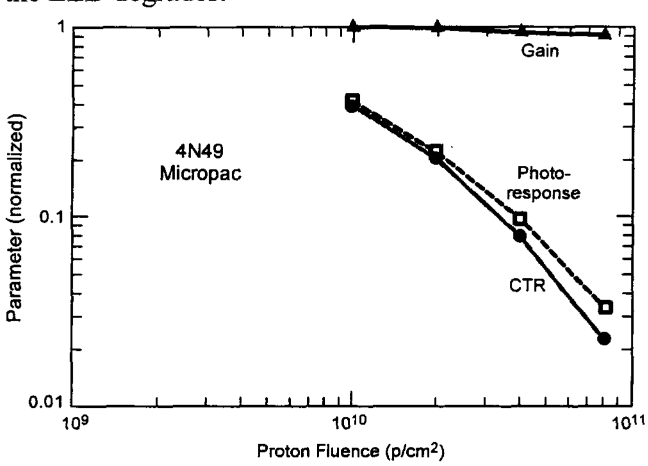


Figure 5. Normalized CTR, photoresponse and gain vs. proton fluence for Micropac 4N49 optocouplers (Date Code 0139).

## III. Discussion

*A. Degradation of the New Optocoupler Devices*

Agilent Technology uses double-heterojunction LEDs, which are less affected by displacement damage compared to the amphoterically doped LEDs uses in older optocouplers [11]. The marked improvement in radiation hardness of the low input current optocouplers is due to two factors: the LED technology and the circuit design. The 4N49 optocoupler uses a single phototransistor, but the Agilent devices use the Darlington configuration shown in Figure 6.

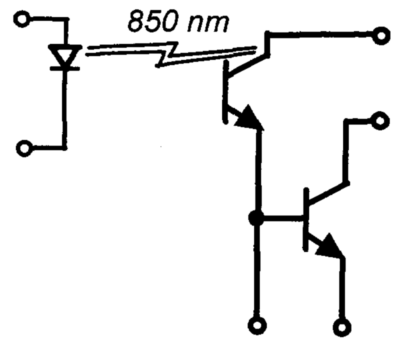


Figure 6. Darlington transistor configuration used for the 6N139 and HCPL-4701 optocouplers.

The first transistor, which is also the photodetector, is connected as an emitter follower. This increases photocurrent by the factor $h_{FE}$, which increases base current in the second transistor by the same factor. Photoresponse measurements cannot be made on the first Darlington transistor with the normal pin configuration, but can be made on the second transistor. However, the currents are increased by the factor $h_{FE}$. That is not the case for the HCNR-200; it uses a basic photodiode.

The ratio of the photoresponse measurement to the LED current of the different types of devices is shown in Table 2. This table does not take the optical efficiency of the LED into account, but it clearly shows that the overall optical-to-electrical efficiency of the new types of optocouplers is substantially improved compared to the older optocoupler types. The overall photoresponse of the HCNR-200 is about five time better than that of the 4N49, taking into account that the LED current is split between the two photodetectors in the dual assembly.

Table 2
Coupling Efficiency of the Four Types of Optocouplers

| Device | LED Current (mA) | Ratio of Photoresponse to LED Current |
|---|---|---|
| HCPL-4701 | 0.04 | 0.36 |
| 6N139 | 0.5 | 0.29 |
| HCNR200 | 1 | 0.0021 |
| 4N49 | 1 | 0.00084 |

The Agilent optocouplers use a sandwich construction method that increases the coupling efficiency, while the 4N49 uses a configuration where the LED assembly is mounted alongside the phototransistor, relying on a polymer coating for light coupling [2].

*B. Annealing*

Although some annealing may also occur in phototransistors, annealing in light-emitting diodes is usually the dominant mechanisms in optocouplers. Annealing in LEDs is strongly injection dependent, and it has been shown that LED damage remains stable over periods of several months for unbiased devices [11], even for LEDs that are strongly affected by injection-enhanced annealing. As soon as current is applied to the device, the annealing process begins. Older work on discrete LEDs has shown that a current-time product (charge) of about 0.01 C is sufficient to cause significant annealing. Optocoupler measurements need to be planned to take this sensitivity into account. Although annealing may ultimately help in space applications, it is effectively an interference during characterization measurements, and can lead to inconsistent results.

Not all LED technologies anneal. Annealing measurements of the Agilent Technologies optocouplers over time periods of a few weeks indicate that they anneal very little, even when forward bias is applied to the LED for extended periods. This is consistent with older results for discrete double-heterojunction LEDs [6,11]. LEDs that are amphoterically doped with silicon have been shown to be the most sensitive to annealing effects.

Annealing measurement also provide a way to separate LED degradation from photoresponse degradation in optocouplers (it is not possible to separate these factors without special measurements on partially depackaged devices). Photoresponse will be unaffected by annealing.

*C. Performance of the Optek 4N49 over Extended Time Periods*

Previous work showed that degradation in older versions of the 4N49 optocoupler was dominated by degradation of the internal light-emitting diodes [2], which are amphoterically doped. This produces very efficient LEDs [12], but they are extremely sensitive to displacement damage because of the broad transition region from p- to n-material that is formed by gradually altering the temperature during the growth phase. Consequently, these devices require long carrier lifetimes for operation, which is the reason they are so strongly sensitive to displacement damage.

A comparison of degradation of several lots of 4N49 devices is shown in Figure 7. There is considerable difference in the radiation sensitivity of different lots, and this appears to be related to the light-emitting diodes, based on previous work with discrete LEDs and phototransistors as well as photoresponse and gain measurements that were made on the more recent 4N49 lots.

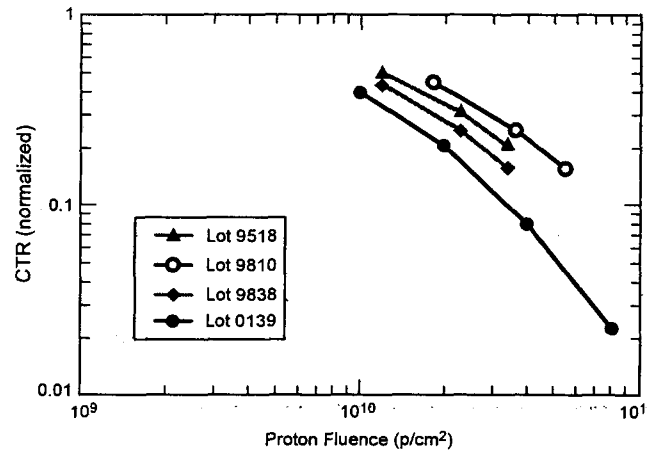


Figure 7. Normalized CTR degradation for various lots of the Micropac 4N49 over a seven-year time period.

The lot with the best performance had much higher CTR values (the mean CTR with $I_F = 1$ mA was above 10 for that lot, even though the minimum guaranteed CTR is 2). The increase in CTR allows the phototransistor to operate in a more efficient region, reducing the effect of current dependence of transistor gain as the LED output degrades. The photoresponse, which was measured for three of the four lots, was also higher for the lots with better radiation performance.

The interplay between light output and radiation damage is cause for concern, because a device with reduced initial light output will be considerably more sensitive to displacement damage degradation than the rest of the devices within a device lot. This is particularly the case for the 4N49, where LED degradation dominates because the phototransistor is forced to operate at very low collector current with reduced efficiency. As shown in Figure 7, the light output can decrease by a factor of 10 or more. Although this interplay is still present for devices with improved LEDs, it is less apparent because the LED light output is relatively less.

## VI. Conclusions

This paper compares radiation damage in a new series of basic, open-collector optocouplers with that of older devices. These new device designs have much higher current transfer ratios compared to the older 4N49, and can be irradiated to levels that are more than a factor of ten higher than the 4N49 before significant degradation occurs in a proton environment.

Gain and photoresponse degradation was similar for the new optocouplers and the older 4N49 devices, providing direct evidence that LED degradation is the main reason for the improved radiation performance.

Analysis of the results and comparison with a more elementary type of optoisolator in this same series of devices shows that the increased CTR is due to the circuit design, which incorporates a Darlington transistor. The improved radiation performance occurs because the Agilent devices use double-heterojunction LEDs. Even though one of the devices uses very low drive current – 40 μA – it is still at least an order of magnitude more resistant to proton damage than the 4N49, which requires a drive current of 1 mA. Thus, these devices are promising candidates for space applications.

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